Integrating nuclide specific and dose rate based methods for airborne and ground based gamma spectrometry.

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Results of joint airborne survey work conducted by SUERC and JAEA are presented, for areas to the north and south of Fukushima Daiichi using four different airborne survey systems, cross calibrated at reference sites in Scotland and near Namie. Airborne measurements were made at a series of different survey heights using three high volume NaI based spectrometers, and for the first time using a high resolution system based on the Ortec IDM HPGe spectrometer. The JAEA data sets were analysed using the same methods applied to national scale mapping in Japan since the accident. The SUERC data sets were analysed using nuclide specific approaches validated in the European ECCOMAGS project. The data presented on a digital terrain model show marked correspondence with landscape features, which both suggest the initial deposition processes, and indicate trajectories for future re-deposition by natural processes. All data sets are traceable to each other, and to the ground based calibration sites. Nuclide specific inventories have been defined, which can serve as a future reference to evaluate environmental change.

Key Words: *Airborne monitoring, Manned helicopter, Accident of Fukushima Daiichi NPS*

1. Introduction: A multiscale problem

As recovery progresses more quantitative means to account for radionuclide inventories in complex environments are needed. This is a significant multi-scale problem. Contamination ranges from national and regional (100-1000 km), through local (1-10 km), and site specific (1-100m) spatial scales. Yet the physical, chemical and biological behaviour of radionuclides is influenced by speciation and processes determined at sub-microscopic scales. Comprehensive knowledge on all scales is needed to predict future behavior, and enhance the knowledge base for a managed recovery. Moreover, since 2011, measurements have been conducted by different institutions using diverse methods. It is important to integrate and cross validate data and methods to enhance confidence in the outcomes.

Here we present recent collaborative work between SUERC and JAEA[(1)] which aimed to (a) establish traceable ground to air comparisons for airborne gamma spectrometry (AGS) in Japan, and (b) assess nuclide specific AGS methods in conjunction with methods based on dose rate apportionment.

2. Joint airborne surveys in November 2014

Airborne surveys were conducted in November 2014 with UK and Japanese systems. The survey areas are shown in Figure 1. Areas 1 and 5 are mountainous and forested and were surveyed at nominal heights of 150m (500 feet) , 300m (1000 feet) and 450 m (1500 feet).

Figure 1: Map of survey areas for November 2014 joint airborne survey. Image: Landsat ©Google 2015

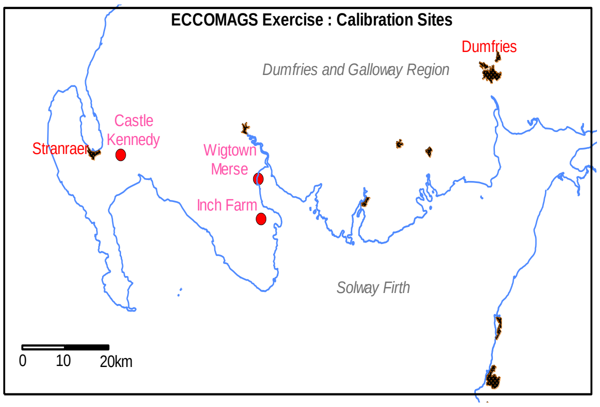

Figure 2: Location of calibration sites in SW Scotland.

For areas 1 and 5 each survey comprised 180 line km, and took 80-100 minutes of flight time.

SUERC deployed two NaI(Tl) spectrometers, of 16 litre (the "Rack" system) and 4 litre (the "Black Box" system) volume, plus a system developed with the Ortec IDM-200V self-cooled hyperpure Ge spectrometer (the "IDM" system), and tested for the first time in the air during this project. These systems were extensively tested in the UK prior to shipping to Japan; the rack and black box systems being flight calibrated at the ECCOMAGS sites in SW Scotland. In Japan the SUERC spectrometers were bench tested in JAEA's laboratory at Fukushima University, and then installed in a Bell 412 helicopter operated by Aero Asahi, and used for national mapping in Japan. JAEA also conducted measurements using Radiation Solutions 12 litre NaI(Tl) spectrometers. The systems were powered independently from the aircraft, and combination of GPS data and a digital elevation model used for ground clearance estimation.

3. Data analysis approaches

SUERC data sets were analysed using nuclide specific approaches validated in the European ECCOMAGS project[2,3]. For the NaI(Tl) data nuclide specific energy regions were integrated, and standard approaches applied based on background subtraction, matrix stripping (using matrices derived from measured and simulated spectra for each radionuclide or series to deconvolve interferences), altitude standardization and conversion to nuclide specific activities for ^{137}Cs and ^{134}Cs (in kBq m^{-2}) and naturally occurring nuclides ^{40}K, ^{214}Bi, ^{208}Tl (in Bq kg^{-1}). High resolution data were calibrated using specific gamma ray lines.

JAEA has conducted airborne surveys using manned aircraft since 2011[4,5] contributing extensively to the MEXT programme of national surveys. Dose rate mapping methods have been adopted in Japan using the "non-natural" dose rate approach, with apportionment to ^{137}Cs and ^{134}Cs activity estimates based on conversion between dose rate and activity per unit area using coefficients from ICRU53[6], and knowledge of mean isotope ratios.

3.1 Ground to air calibration at reference sites Scotland (UK)

Reference sites provide traceability between soil samples, in-situ, backpack, and airborne gamma measurements. The SUERC spectrometers were flight tested at the ECCOMAGS intercomparison sites in SW Scotland[2,3] (Figure 2). Table 1 shows the airborne and ground based data on these sites, and establishes international traceability to the work. For ^{137}Cs a mean mass depth of 8.5 g cm-2 which matches the reference depths for Inch Farm (IF) and Castle Kennedy(CK), where radiocaesium was deposited by atmospheric processes, reasonably well. At Wigton Merse the activity was deposited

Table 1: Results for the ECCOMAGS calibration sites measured in September 2014, together with reference values updated to 2014.

.Site	Value	^{137}Cs Activity kBq m^{-2}	^{137}Cs Mass depth g cm^{-2}	^{40}K Bq kg^{-1}	^{214}Bi Bq kg^{-1}	^{208}Tl Bq kg^{-1}	Dose rate µGy h^{-1}
WG	Measured	(56 ± 1)	(8.5)	333 ± 5	18.6 ± 0.9	5.8 ± 0.1	0.053 ± 0.001
	Reference	170 ± 10	26	383 ± 13	13.4 ± 0.4	7.5 ± 0.3	
IF	Measured	14.6 ± 0.5	8.5	358 ± 5	24.4 ± 1.1	7.8 ± 0.1	0.039 ± 0.001
	Reference	16.9 ± 0.8	8.5	376 ± 14	23.8 ± 1.9	9.9 ± 0.6	0.054 ± 0.003
CK	Measured	4.3 ± 0.2	8.5	207 ± 4	11.3 ± 0.7	4.2 ± 0.1	0.023 ± 0.001
	Reference	4.8 ± 0.2	12.8	270 ± 13	14.4 ± 0.7	6.5 ± 0.5	0.033 ± 0.005

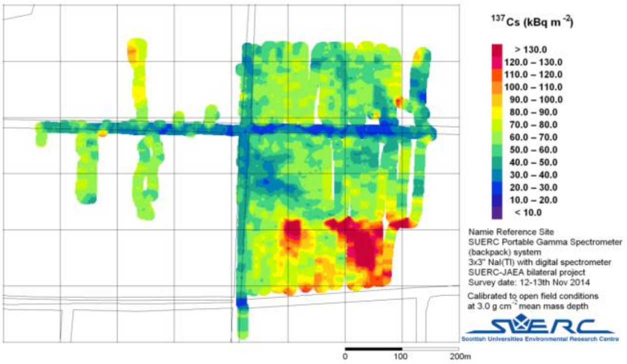

Figure 3: Backpack survey of the Namie calibration site, November 2014. Note the lower activity levels along roads, and the higher activity levels in the SE quadrant, which had not undergone active remediation at time of survey

by tidal inundation of sediments contaminated by past marine discharges from the Sellafield reprocessing site. It shows a. pronounced subsurface maximum with mean mass depth of 26 g cm-2 (2014 value) resulting in a significantly different Cs calibration factor, as previously observed[2].

Fukushima (Japan)

A reference site was sampled near Namie in November 2014 ahead of the airborne work. 31 soil cores were collected on an expanding hexagonal pattern designed to accommodate spatial heterogeneity[(7)]. They were subdivided into depth intervals, dried and prepared for later laboratory analysis by high resolution gamma spectrometry. Backpack mapping 1-100m scale, also showing the effects of ongoing remediation, and self-cleaning of road surfaces. Dose rates were measured at ground level by JAEA. Table 2 shows the agreement between sample based and airborne results from the site, establishing nuclide specific traceability between ground sampling and airborne observations for the first time in Japan.

4 Results

Figure 4 shows spectra and altitude corrected count rate data for ^{137}Cs at different heights above the Namie calibration site for the 16 litre (rack) system. As expected (eg the half depth for 662 keV radiation in air is ~72 m) the spectra show marked reductions peak intensities and relative increase in scattered components with increasing height. Altitudecorrected peak count rates show increasing dispersion with height, reflecting these features, confirming that measurement precision for nuclide specific mapping is strongly dependent on ground clearance.

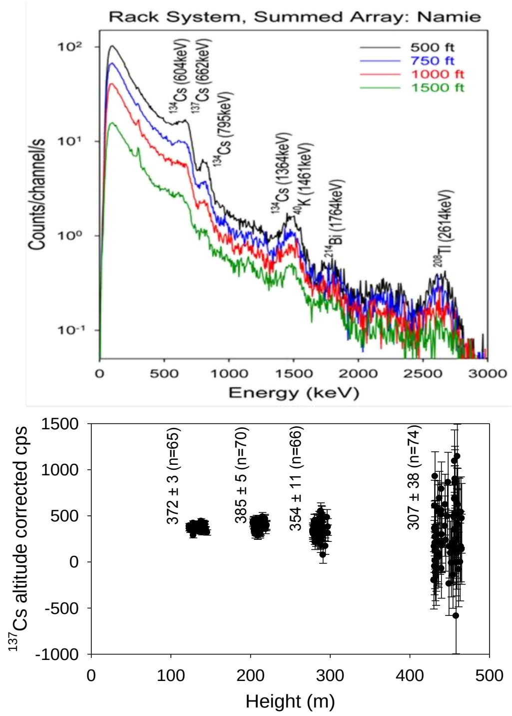

Figure 4: Mean spectra (top) and altitude corrected count rates (below) recorded at different heights above the Namie calibration site, using the SUERC rack system.

Full results for all survey areas are given in Sanderson *et.al.* 2015[(1)]. Here we illustrate some of the data from area 5 (SW of FDNPP). Average spectra for the three SUERC systems for the 500ft survey of this area are shown in Figure 5. These show the difference in relative efficiency between the

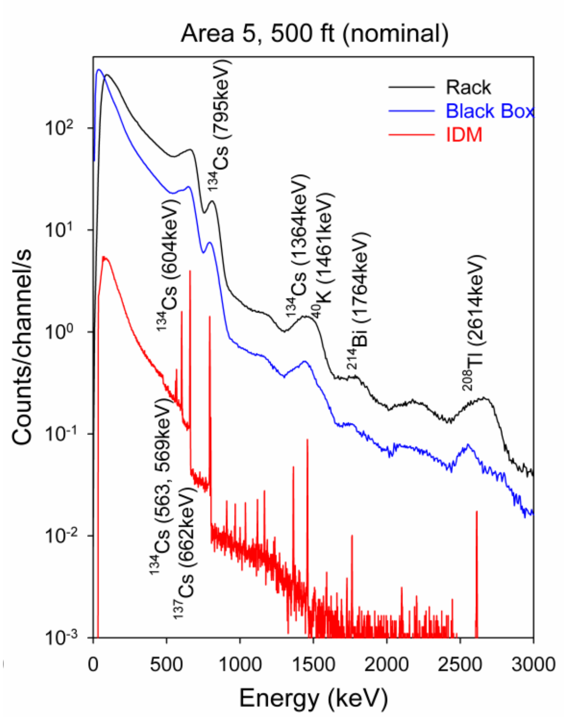

Figure 5: Average spectra recorded with the three SUERC systems for the 500ft survey of Area 5.

Table 2: Results of measurements on the Namie reference site at different ground clearances. For ^{137}Cs and ^{134}Cs a mean mass depth of 3 g cm-2 was applied..

System		^{137}Cs kBq m^{-2}	^{134}Cs kBq m^{-2}	^{40}K Bq kg^{-1}	^{214}Bi Bq kg^{-1}	^{208}Tl Bq kg^{-1}	Dose rate μGy h^{-1}
Rack	500ft	73.3 ± 0.7	19.3 ± 0.5	258 ± 6	22.3 ± 2.0	7.0 ± 0.2	0.185 ± 0.001
	750ft	75.8 ± 1.0	18.7 ± 0.6	243 ± 10	24.8 ± 2.9	6.5 ± 0.3	0.186 ± 0.001
	1000ft	69.8 ± 2.2	19.6 ± 1.0	268 ± 12	20.6 ± 4.7	6.6 ± 0.4	0.182 ± 0.001
	1500ft	60.5 ± 7.5	21.5 ± 2.2	278 ± 26	18.6 ± 11.7	8.1 ± 0.6	0.193 ± 0.002
Black box	500ft	74.9 ± 1.5	16.5 ± 0.7	219 ± 14	23.4 ± 2.2	6.5 ± 0.5	0.182 ± 0.003
	750ft	80.3 ± 1.7	16.6 ± 1.0	235 ± 15	20.6 ± 3.8	6.5 ± 0.8	0.189 ± 0.002
	1000ft	66.2 ± 3.1	17.5 ± 1.7	198 ± 20	25.6 ± 5.1	5.6 ± 1.1	0.176 ± 0.002
	1500ft	60.9 ± 9.2	11.4 ± 3.3	220 ± 44	47.2 ± 8.4	3.1 ± 2.2	0.176 ± 0.004
JAEA (σ=3)	500ft	61.5 ±5.1	20.1 ±1.7	-	-	-	0.183 ± 0.015
Reference		66.6 ± 6.2	17.3 ± 1.6	298 ± 7	22.7 ± 0.8	10.0 ± 0.2	0.182 ± 0.009

systems, and also the much higher spectral resolution of the HPGe detector allowing the quantification of line specific count rates without the use of a stripping algorithm. The use of the different discrete peaks for ^{137}Cs and ^{134}Cs in the HPGe spectra allows for quantification of isotope ratio and mass depth. Figure 6 compares dose rate and ^{137}Cs estimates for the SUERC rack and JAEA 12 litre system, showing similar deposition patterns, and inventories in TBq (Table 3).

Figure 7 compares high volume (16 litre) with low volume (4 litre) NaI systems with the Ge based IDM spectrometer in Area 5. Positions and activity concentrations correspond well, with 150 m (500 feet) ground clearance, and the data confirm the first use of IDM systems for airborne mapping.

The data, on digital terrain models (Figure 8), identify wet and dry deposition areas, and suggest future movement of activity within valley catchments

5. Discussion

Collaborative work between JAEA and SUERC has established traceability between airborne and ground based measurements through measurements at calibration sites in SW Scotland developed for an international intercomparison exercise and the development of a calibration site near Namie. Reference values have been defined from laboratory measurement of samples, and a backpack survey used to evaluate spatial variability. This has highlighted the self-cleaning of road surfaces, and the effect of ongoing site remediation within a dynamic environment. Initial comparisons have been made between airborne measurements with spectrometry systems utilizing spectral analysis methods to directly quantify radionuclide activity concentrations, and with dose rate apportionment methods. These approaches reproduce the general features of the common survey areas, and inventories, however nuclide specific approaches have advantages in providing independent means of registering

Table 3: Inventories of ^{134}Cs and ^{137}Cs in each of the two survey areas determined from the different NaI(Tl) systems at three different ground clearances.

		Rack Inventory (TBq)		Black Box Inventory (TBq)		JAEA Inventory (TBq)	
		^{137}Cs	^{134}Cs	^{137}Cs	^{134}Cs	^{137}Cs	^{134}Cs
Area 1	500ft	43.79 ± 0.03	14.74 ± 0.01	40.45 ± 0.03	12.39 ± 0.02	29.8	9.65
	1000ft	41.13 ± 0.07	11.37 ± 0.02	30.67 ± 0.08	8.81 ± 0.03	32.6	10.5
	1500ft	39.98 ± 0.25	10.99 ± 0.06	27.67 ± 0.26	7.24 ± 0.09	26.3	8.52
Area 5	500ft	39.77 ± 0.02	13.23 ± 0.01	39.74 ± 0.03	12.53 ± 0.01	30.4	9.84
	1000ft	40.03 ± 0.05	11.33 ± 0.02	37.77 ± 0.05	5.67 ± 0.02	27.8	8.99
	1500ft	44.72 ± 0.17	12.67 ± 0.05	30.83 ± 0.19	8.13 ± 0.07	25.9	8.37

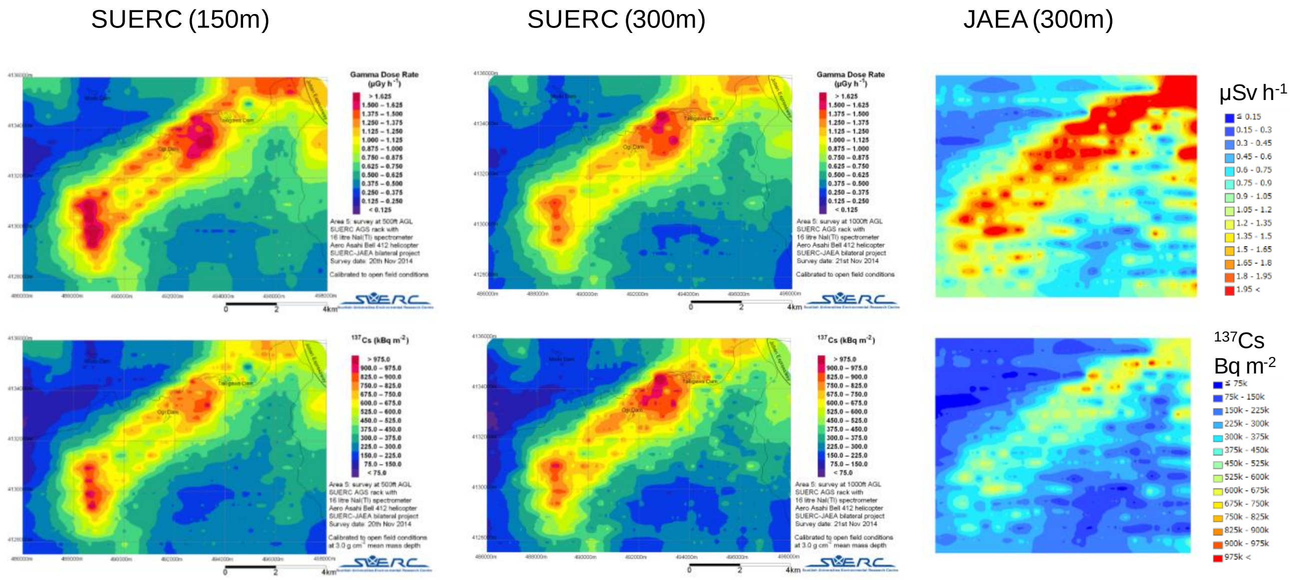

Figure 6: Dose rate and ^{137}Cs distribution in area 5 measured with the SUERC rack system at 150m and 300m ground clearance, and with the JAEA system at 300m

isotopic variations, and placing the radiocaesium and naturally occurring nuclides in context. There is scope for further analysis of the potential for applying nuclide specific methods to the JAEA data sets and to earlier national surveys to build 4D models for the nuclide migration in these upland areas. The use of landscape 3D drapes with the lowest altitude data sets show remarkable correspondence to landscape features, including enhanced signals in valley bottoms in area 1, and topographically significant positioning of activities in area 5 which are suggestive both of the depositional processes and likely trajectories for long term migration of activity. Again there is scope for further application of these approaches to visualization of the activity distributions and movements within complex and dynamic environments in Fukushima. The work was successful in establishing the ability of UK and Japan teams to produce high quality airborne data sets using diverse systems. It also verified, for the first time, the potential of new IDM technology for AGS

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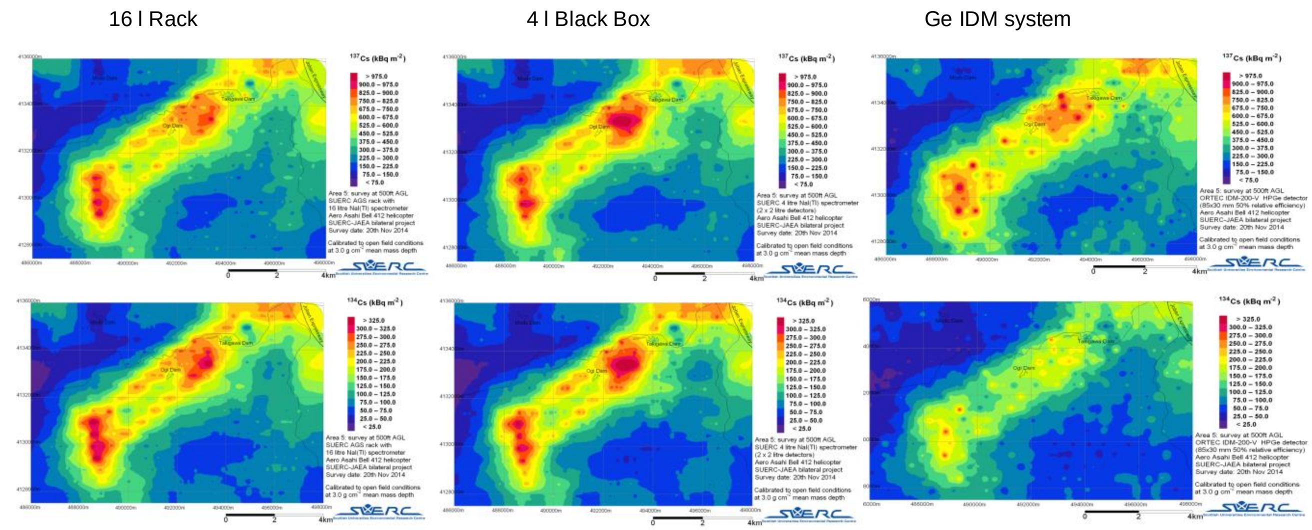

Figure 7: Comparison between the three SUERC systems at 150m for area 5.

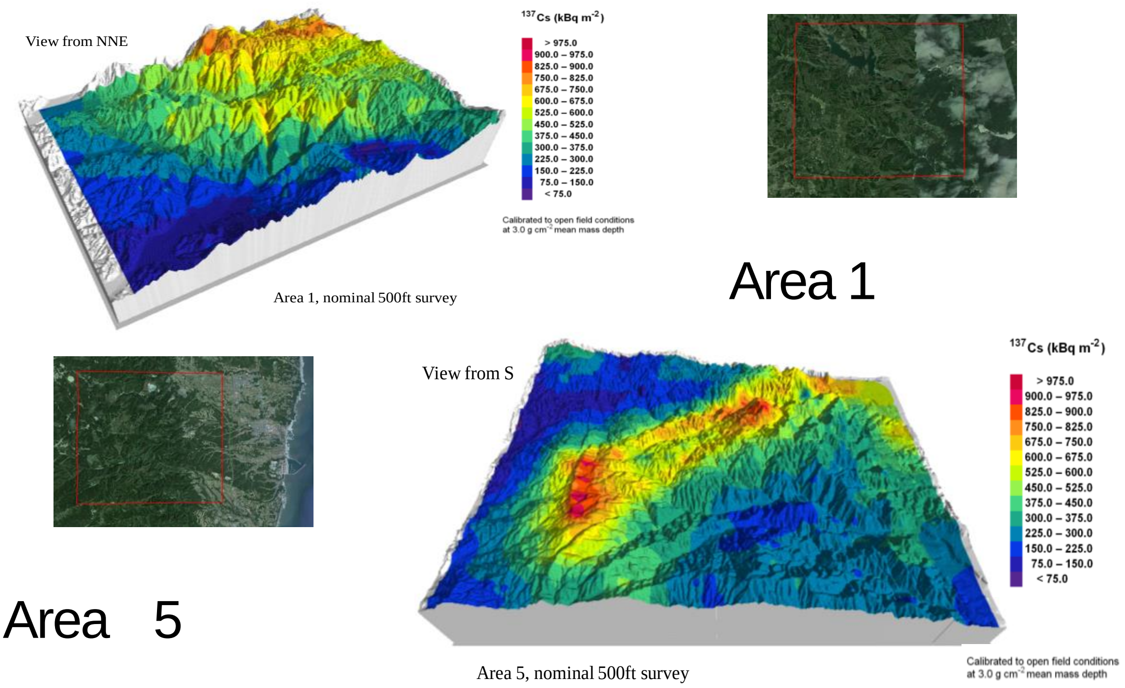

Figure 8: ^{137}Cs activity distribution on 3D landscape models for area 1 (top) showing increased concentration in river valley floors, and area 5 (bottom) showing deposition on mountains. Image: Landsat ©Google 2015

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